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STRATIGRAPHY, TAPHONOMY, AND NEW DISCOVERIES FROM THE UPPER JURASSIC (MORRISON FORMATION: BRUSHY BASIN MEMBER) PETERSON QUARRY, CENTRAL NEW MEXICO

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Abstract—The Upper Jurassic Peterson quarry, located in Bernalillo County, central New Mexico, is New Mexico's most extensive and productive Jurassic dinosaur locality. The quarry is developed in the upper Brushy Basin Member of the Morrison Formation, approximately 26 m below its contact with the overlying Jackpile Member. Bones occur low in a 3.3-m-thick sequence of well-indurated, trough-crossbedded, subarkosic sandstone. Preserved elements range from scattered bones to articulated assemblages of bones from a single individual, and the long bones are preferentially oriented along a generally east-west-trending axis. The occurrence of associated-to-articulated bones in a trough-crossbedded sandstone underlying a floodplain mudstone suggests deposition of the fossils in the mixed fill of an abandoned channel in a typical Brushy Basin Member fluvial system. Particularly important dinosaurs from the Peterson quarry include a large (1100 mm estimated femoral length) *Saurophaganax*-like allosaurid theropod and the anterior portion of a diplodocid skull and lower jaws similar to *Diplodocus*. This specimen is one of less than a dozen Morrison Formation diplodocid skulls known and is particularly important because it is: (1) the only Jurassic sauropod skull material from New Mexico; (2) could represent a genus and/or species of Morrison diplodocid from which skull material is not yet known; and (3) provides insight into the replacement pattern of diplodocid teeth.

INTRODUCTION

Previous authors have often noted that New Mexico's record of Jurassic vertebrates lacks the rich Morrison Formation quarry faunas known from other western states such as Wyoming, Utah, Colorado, and Oklahoma (e.g., Lucas and Hunt, 1985; Lucas and Heckert, 2000). Until 10 years ago, almost all known New Mexican Morrison Formation localities were isolated occurrences of an incomplete, single individual dinosaur (Rigby, 1982; Gillette, 1991). These are very different from the rich bonebeds at, for example, Como Bluff, Garden Park, Dinosaur National Monument, Cleveland-Lloyd, and the Stovall quarries (Dodson et al., 1980; Foster, 2000). Here, we document New Mexico's first Morrison Formation dinosaur bonebed, with multiple elements preserved from at least two taxa and perhaps several individuals. This locality, New Mexico Museum of Natural History and Science locality 3282, is in the Brushy Basin Member of the Morrison Formation in Bernalillo County, central New Mexico (Fig. 1). Locality 3282 is known informally as the "Peterson quarry" and is New Mexico's strongest candidate at this time to yield a large and important sample of Morrison Formation dinosaurs.

Here, we document the history of study of the quarry, its stratigraphy and taphonomy, and highlight some of the most significant fossils recovered from the quarry. In this paper, NMMNH refers to the New Mexico Museum of Natural History and Science.

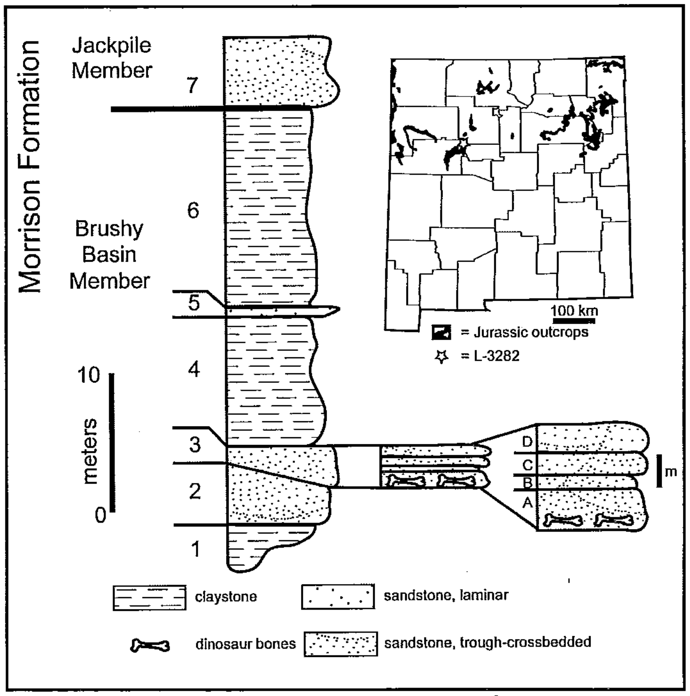

FIGURE 1. Location map and stratigraphic section of the Peterson quarry (NMMNH L-3282).

HISTORY OF STUDY

The general area of the Peterson quarry was initially discovered by one of us (Rodney Peterson) while prospecting for uranium in the 1960s. Collectively, the Petersons and Dan D'Andrea began leading the first of more than 100 trips to the site in 1989. Since that time, they and other NMMNH volunteers have dedicated more than 5200 hours of labor documenting and excavating almost 50 jackets and more than 100 bones from the Peterson quarry (Fig. 2), with excavations continuing at this time.

To date, the fauna of the Peterson quarry has been mentioned in summary articles by Hunt and Lucas (1993), Lucas et al. (1996), Foster (2000) and Lucas and Heckert (2000). Williamson and Chure (1996) described the partial pelvis, hind limb, and cau-

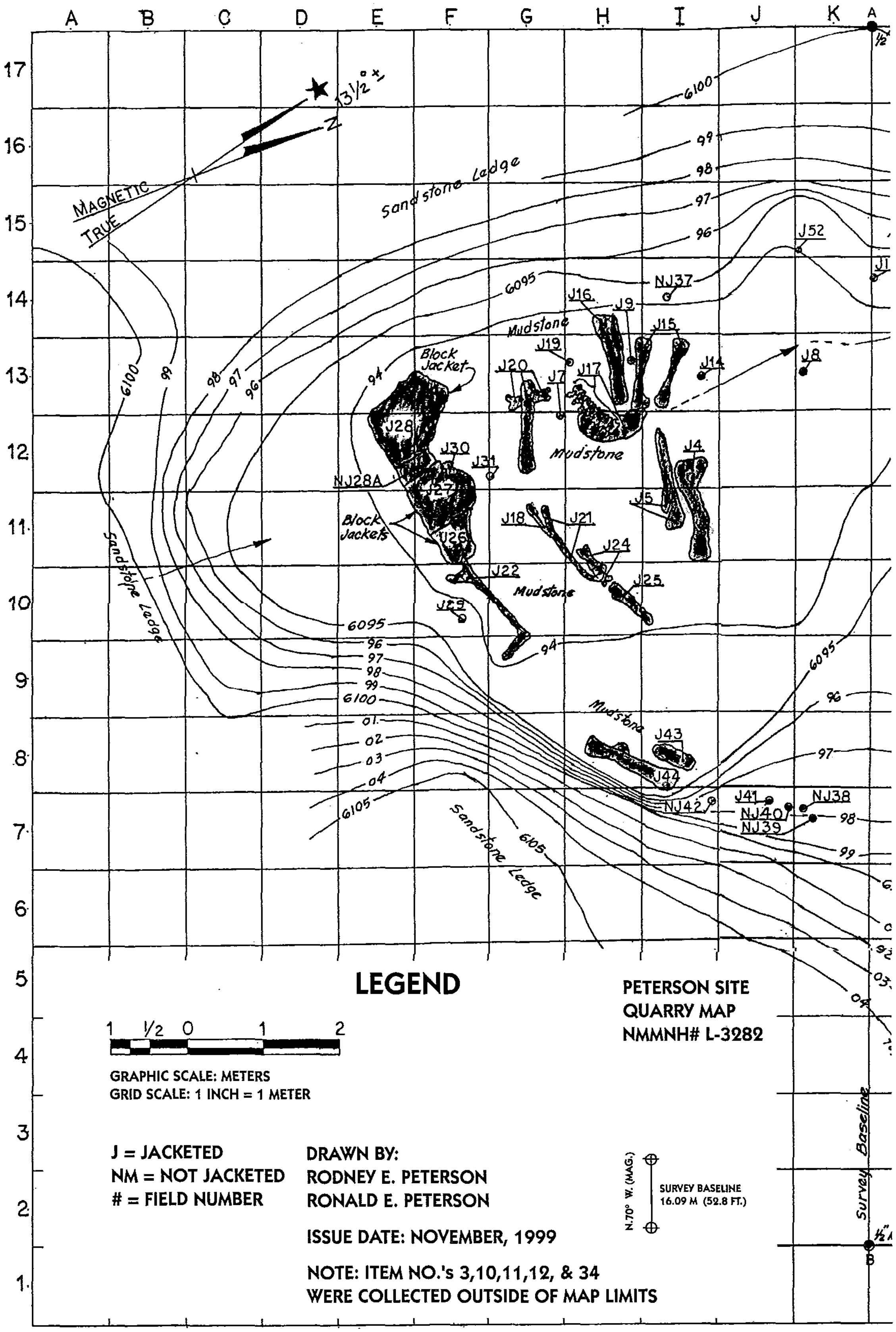

FIGURE 2. (Both pages) Detailed quarry map prepared by Rodney E Peterson and Ronald E. Peterson. Grid squares are 1 m^2. J numbers refer to jacketed specimens, NJ numbers refer to specimens removed without jacketing. Numbers match those used in other figure captions.

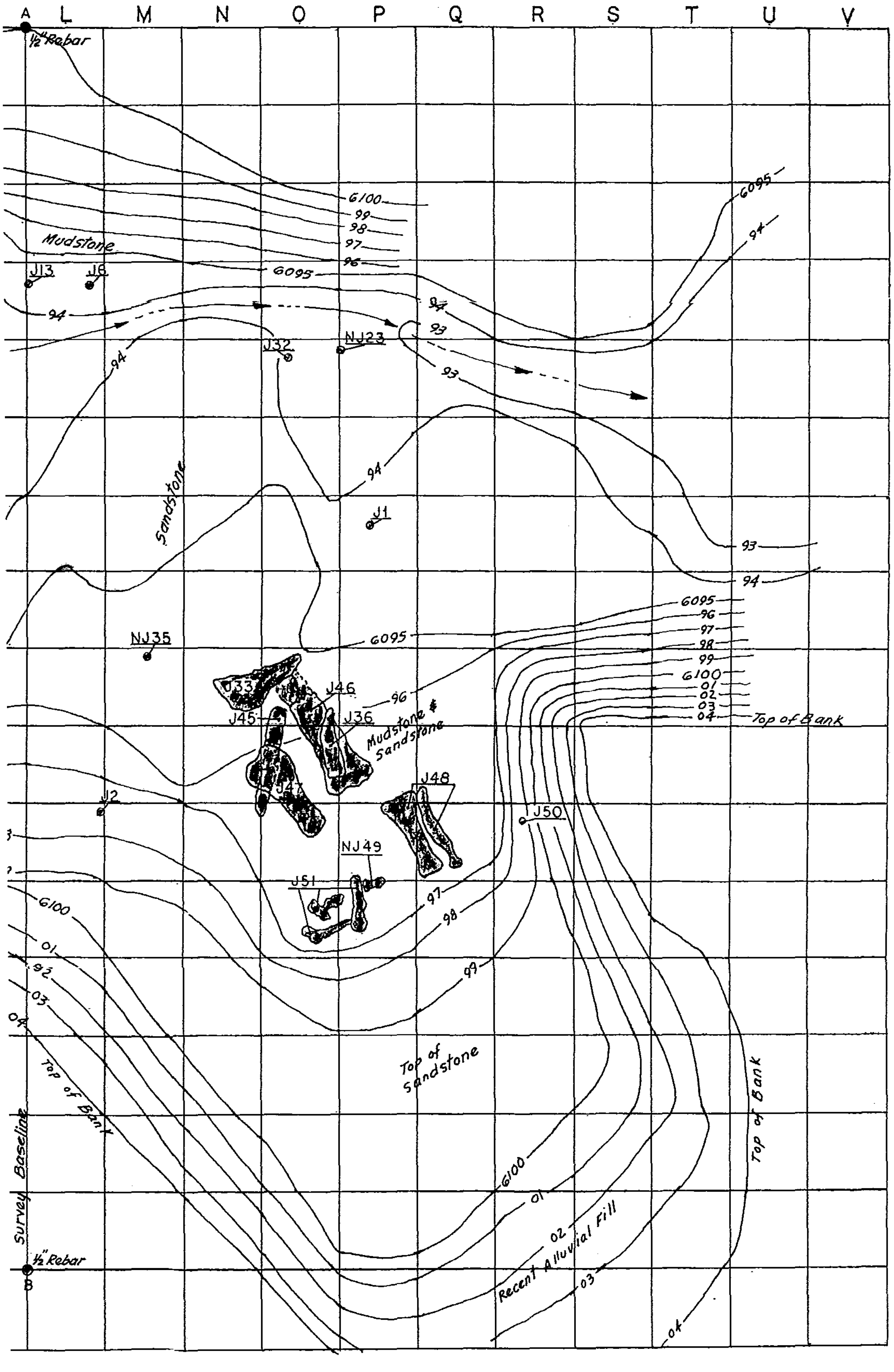

FIGURE 2. (Continued) Detailed quarry map prepared by Rodney E Peterson and Ronald E. Peterson. Grid squares are 1 m². J numbers refer to jacketed specimens, NJ numbers refer to specimens removed without jacketing. Numbers match those used in other figure captions.

dal vertebrae of a large allosaurid from the Peterson quarry, but did not address the stratigraphy or taphonomy of the site. Recently, we (Peterson et al., 1999a,b) have begun to summarize data on the stratigraphy and taphonomy of the Peterson quarry, and we present those results in more detail in the following sections.

STRATIGRAPHY

In north-central New Mexico, the Morrison Formation consists of three members (in ascending order): Salt Wash, Brushy Basin, and Jackpile (Anderson and Lucas, 1996, 1997; Lucas and Anderson, 1998; and references cited therein). Of these, the Salt Wash and Brushy Basin members are readily correlated throughout the Morrison outcrop belt in the Western Interior (Anderson and Lucas, 1998). The Peterson quarry is located in the Brushy Basin Member of the Morrison Formation, as are almost all large Morrison Formation dinosaur quarries (Turner and Peterson, 1999). The quarry lies in the floor of an arroyo approximately 26 m below the contact of the Brushy Basin Member with the overlying Jackpile Member of the Morrison Formation (Fig. 1).

Most, if not all, of the dinosaur bones are found in a 1.1-m-thick sandstone lens that overlies and fills scours in less-well indurated, underlying sandstone (Figs. 2-3). The bone-bearing sandstone is a well indurated, yellowish-gray, fine- to coarse-grained, subangular, poorly sorted subarkose. This unit is trough-crossbedded with some clay-pebble conglomerate clasts at the base of trough sets. Some thin (< 5 cm thick), discontinuous, sub-meter-scale mudstone lenses are also present. Overlying the bone-bearing sandstone is a 2.2-m-thick series of 0.6-0.9-m-thick sandstone beds of broadly similar lithology. All of these sandstones are subarkosic, although grain size and sorting vary widely. We provide a detailed description of the measured section illustrated in Figure 1 in the Appendix.

TAPHONOMY

The majority of the fossils from the Peterson quarry consist of disarticulated and partially articulated limb bones, vertebrae, and ribs with a strong east-west orientation (Figs. 2-3). The alignment of the bones approximately parallels the paleocurrent direction indicated by northwest-dipping trough-crossbeds in the sandstone body that contains the bones. However, the large size of the bones and an apparent lack of abrasion suggest a relatively short transport distance. It is of interest that the sauropod bones show a less strongly preferred orientation than do the allosaurid bones, perhaps due to differences in bone size and, more importantly, density.

The close proximity of the bones to the lithologic transition from trough-crossbedded sandstone to a mudstone suggests deposition of the fossils in an abandoned channel. As the stream slowly

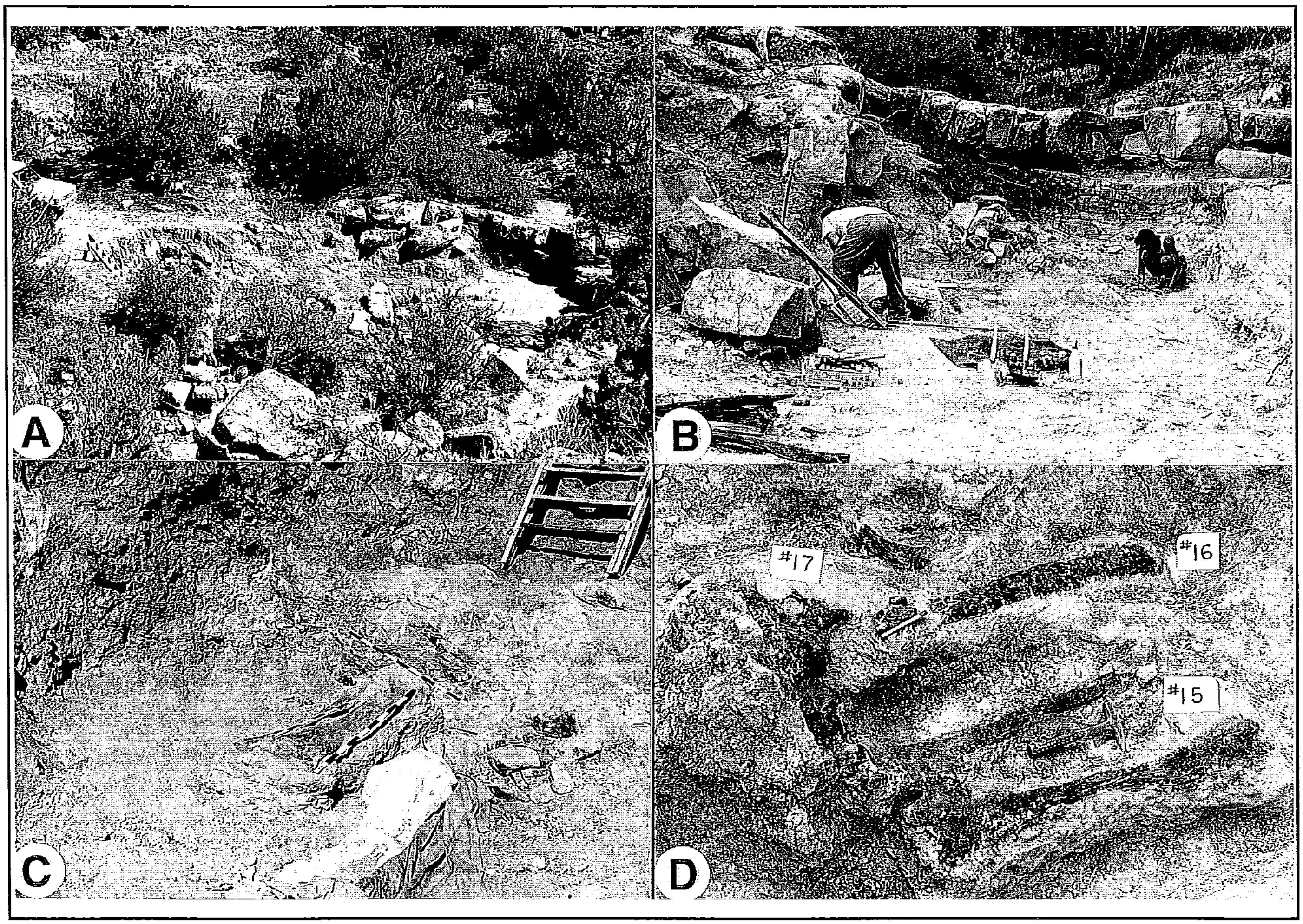

FIGURE 3. Photographs of the Peterson quarry. A, Overview of the quarry on 18 July 1999. The principal bonebed is the arroyo bottom partially filled with water. B, View in the quarry on 2 July 1995 showing trough-crossbedded, channelform sandstone geometry of bone-bearing sandstone interval; man on left is covering a pedestaled bone. C, Sauropod tibia and fibula in the quarry, 16 May 1999. D, Articulated theropod bones in the quarry, 22 October 1994.

aggraded its bed prior to avulsing, the bones that were deposited were covered relatively quickly with channel sands, followed by the deposition of overbank mudstones. These events would not only allow stream flow to orient the bones, but would also increase the potential for preservation of the fossils. However, contrary to expectations for a channel-fill deposit, there is little in the way of organic material present in the overlying mudstones.

By comparison, the mass accumulation at Dinosaur National Monument is considered to have developed as a channel-lag deposit (Morris et al., 1996). The bones were deposited in a confined channel during several depositional events and show a strong preferred orientation. The environment of deposition has been inferred to be a meander in a fluvial system where bones accumulated during several episodes of confined flow (Morris et al., 1996). In this case, the bones were deposited near the base of an active channel. In the channel-fill processes associated with the Peterson quarry, the bones are instead associated with the mixed fill of an abandoned channel.

Notably, many of the long bones are not horizontal and have a depositional dip of as much as 8 degrees. This is best illustrated by the contours in Figure 2, which show that the general trend of these depositional dips is down to the northwest. We interpret these sloping beds to represent some form of bar deposit.

In general, the sedimentology of the bone-bearing deposit and the orientation of the bones in three-dimensional space well match the taphonomy of other fluvial Morrison deposits (Dodson et al., 1980). Although non-bone organic detritus is rare to completely lacking, the orientation of the bones in a trough-crossbedded sandstone corresponds well to the characteristics associated with bone deposits in the mixed fill of an abandoned channel (Behrensmeyer, 1988).

PALEONTOLOGY

To date, only the large theropod documented by Williamson and Chure (1996) has been described and illustrated from the Peterson quarry, although Lucas et al. (1996) illustrated some of the diplodocid material described and illustrated here. In the following section we describe the partial skull of a diplodocid sauropod from the Peterson quarry and comment on the significance of this and other fossils from the quarry.

Diplodocid skull

NMMNH P-26084 consists of a partially disarticulated and crushed skull, including an incomplete right premaxilla and maxilla, incomplete left mandible, several palatal? skull fragments, and 33 teeth, all preserved in two matrix blocks (Fig. 4). Of the teeth, 19 are associated with the larger matrix block and 14 with the smaller one. Originally this material was discovered in a float block slumped from the southern wall of the quarry as it was worked in 1989-1995. Because of its proximity to the bone-bearing horizon and the fact that its lithology exactly matches that horizon, we are confident that this specimen was derived from the main quarry level. This and associated material correspond to identification numbers 38-41 on Figure 2. Subsequently, in 1998, additional diplodocid teeth and skull? fragments were collected in this area. These currently await preparation at NMMNH.

Diplodocid synapomorphies present in P-26084 include the presence of slender, peg-like teeth that lack labial grooves and a ventrally deflected anteroventral margin of the dentary. Although fragmentary, crushed, and incomplete, this specimen is still significant because: (1) it preserves important features identifying it as a diplodocid, of which less than a dozen skulls are known from the Morrison Formation; (2) additional preparation of associated material should refine this diagnosis and thus could provide information on the skull of a species or even genus for which skull material is not currently known; and (3) the numerous teeth associated with P-26084 include nearly the entire erupted dentition as well as numerous replacement teeth, and thus provide information regarding tooth replacement in diplodocids.

Premaxilla

The right premaxilla is exposed in medial view (Fig. 4A-B). The anterior margin is broad and blunt with four erupted teeth exposed. This well matches published illustrations of *Diplodocus* (Marsh,1884; Holland, 1924; Berman and McIntosh, 1978). The left premaxilla lies on the incomplete left maxilla (Fig. 4A-B). This element is more fragmentary than the right and preserves little additional detail aside from the view of at least 4 replacement teeth in medial view. Only the anterior portions of the premaxillae are preserved. In general, these are blunt as in diplodocids, but relatively narrow, and appear more similar to *Diplodocus* than *Apatosaurus*, although they are not, strictly speaking, diagnostic.

Maxilla

Presently, the incomplete right maxilla is only well exposed in ventromedial view. A single, prominent process projects ventromedially and probably articulated with the palatine. If this inference is correct, this is the palatine shelf of the maxilla as described by McIntosh and Berman (1975). The rounded margin of this bone posterior to the palatine shelf is thus the anterior edge of the antorbital fenestra, and the thin maxilla may be broken near the margin of the subnarial fenestra.

Dentary

The single largest element preserved in P-26084 is the distal left dentary, exposed in ventral view (Fig. 4Z). Although slightly crushed, this bone is clearly slender with a broad and blunt anterior margin and concave ventromedial boundaries, so that paired dentaries would have a "U" shape in ventral view. Importantly, this element preserves a prominent, if crushed, ventral projection at the anterior end of the dentary. This feature was well illustrated in *Diplodocus* by Holland (1924). Furthermore, Upchurch (1998) and Wilson and Sereno (1998) list this feature as a synapomorphy of the Diplodocidae.

Dentition

All or parts of 33 teeth are preserved in association with P-26084. These teeth are slender (much taller than wide) and peg-like. None of the well-preserved teeth preserve labial grooves. Upchurch (1998), and Wilson and Sereno (1998) list slender, peg-like teeth lacking labial grooves as a synapomorphy of the Diplodocidae, thus confirming the diplodocid affinities of this skull.

In general, diplodocids have only 50 or so teeth in the upper and lower jaws (McIntosh, 1990; Christiansen, 2000) and all are confined to the anterior margin of the skull and lower jaws. Thus, the presence of at least 33 teeth, even if some are replacements (see below) suggests that much of the dentition, and ostensibly, the skull, are preserved.

At least 8 of the teeth preserved with the fragmentary premaxillae are clearly unerupted. Because sauropod skulls are so rare, this represents one of the few opportunities to examine the nature and pattern of replacement teeth in a diplodocid.

As mentioned in the description of the premaxilla and illustrated in Figure 4, numerous replacement teeth were present in the upper jaw at the time of the animal's death. Although much recent work has been done on the feeding apparatus and tooth microwear of *Diplodocus* teeth (Barrett and Upchurch, 1994; Calvo,

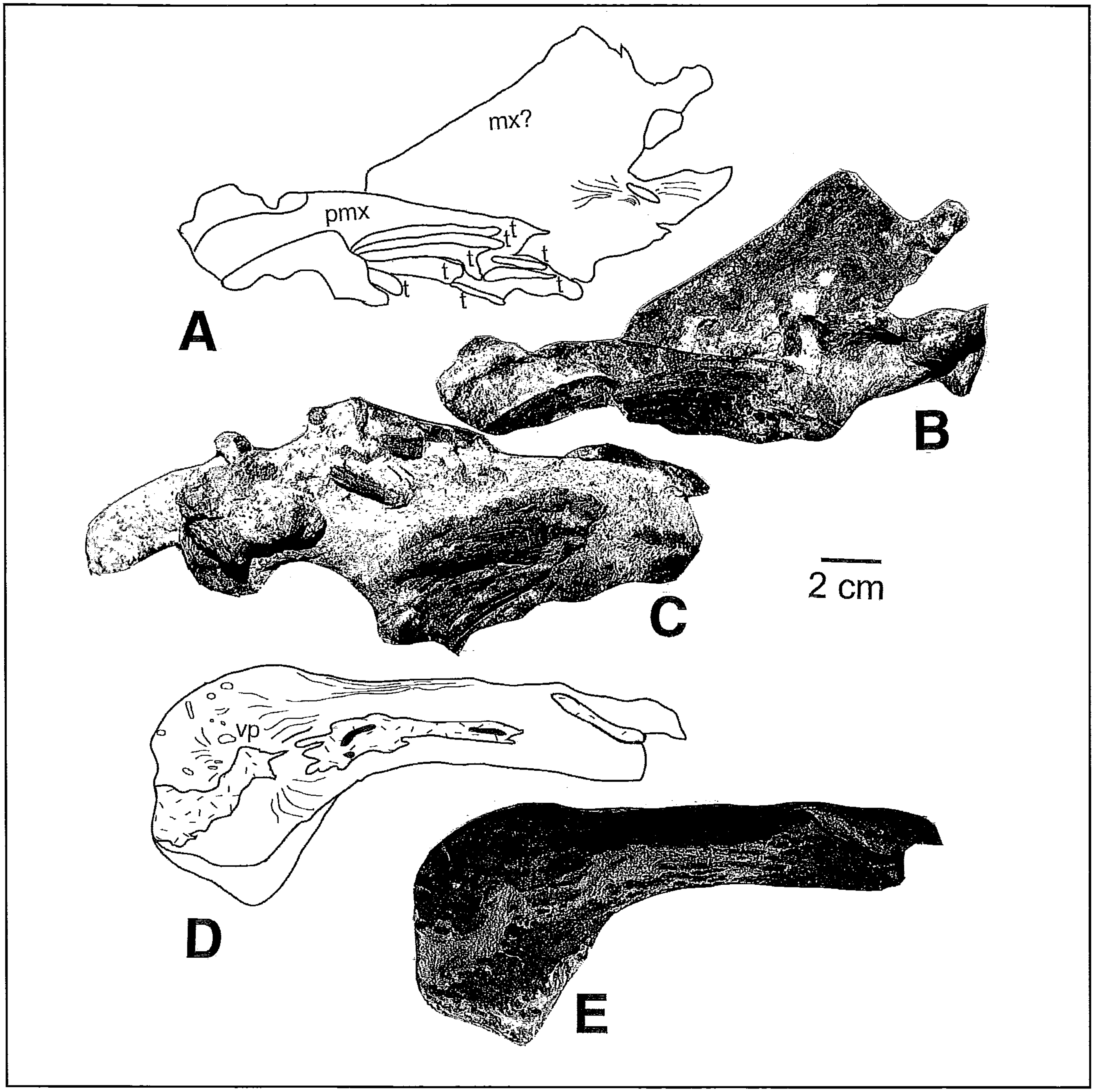

FIGURE 4. Diplodocid skull and lower jaw. A-C, interpretive sketch (A) and photographs (B-C) of matrix block with incomplete, split premaxilla and incomplete maxilla in medial view. D-E interpretive sketch (D) and photograph (E) of the incomplete left dentary, vp = ventral projection.

1994; Fiorillo, 1998; Christiansen, 1999, 2000), these authors generally have not addressed the issue of replacement teeth. The fact that there are as many as two fully formed rows of replacement teeth stacked above the active teeth in the premaxilla suggests that diplodocids were able to readily replace shed teeth, and may in fact have shed teeth frequently.

Other Peterson quarry fossils

Williamson and Chure (1996) described a partial pelvis, hind limbs, and caudal vertebrae of a large allosaurid theropod. As they documented, this specimen, NMMNH P-26083, consists of the posterior half of the right ilium, paired, nearly complete ischia, incomplete right and left femora, left tibia and fibula, several left phalanges, two sacrals? and four caudal centra as well as four chevrons. Williamson and Chure (1996) noted that the elements of P-26083 are larger than any known *Allosaurus* and similar in proportion to *Saurophaganax*. However, no features of the preserved material of P-26083 are autapomorphies of *Saurophaganax*, and there is no overlap of this material with the comparably sized allosaurids *Epanterias amplexus* Cope and *Torvosaurus tanneri* Galton and Jensen (Williamson and Chure, 1996).

Here we briefly highlight a few additional details of P-26083. All of the specimens associated with NMMNH P-26083 were found in close association over a 2 by 4-meter area. These bones were excavated in a series of plaster jackets, with the sacrum and vertebral material in one jacket and ischia and limb bones in individual jackets. Notably, the femur (J4), the tibia and fibula (J5), and both ischia (J15) were all aligned approximately east to west (Fig. 2). Given the orientation of these bones, flow was probably from west to east.

As shown in Figure 2, most of the last 30 or so jackets removed from the Peterson quarry are large limb and rib bones doubtless associated with sauropod dinosaurs. To date, this material has not been prepared and could not be reliably identified in the field, although it clearly contains numerous hind limb elements, several of which may be articulated (e.g., a possible tibia and fibula in jacket 48, just east of a probable femur in jacket 46). We anticipate that further collecting at the Peterson quarry and preparation of the material already collected will allow future refinement of the quarry fauna.

SIGNIFICANCE AND DISCUSSION

In spite of the intense efforts of the last decade, much remains to be known about the Peterson quarry. For example, the only known limits to the bonebed are related to exposure—as more overburden is removed, more fossils are inevitably discovered, especially to the south and east. Thus, we can only guess how extensive the quarry may be. Importantly, preservation appears to improve to the south and east, out of the modern-day arroyo and into less weathered rock.

Clearly the Peterson quarry represents a fluvially-dominated accumulation of bones. The coarse grain size, trough crossbedding, and alignment of long bones a meter or more in length all speak to a substantial fluvial system, probably one that aggraded during the final stages of channel abandonment. The presence of this deposit and numerous similar sandstone bodies in the Brushy Basin Member in the region demonstrate that the Brushy Basin Member in New Mexico represents the deposits of a typical fluvial system with isolated coarse-grained channels separated spatially by fine-grained floodplain deposits. Thus, there is no reason to believe that a large lacustrine system (Lake T'oo'dichi' of Turner and Fishman, 1991) deposited the Brushy Basin Member of the Morrison Formation of northern New Mexico.

In a comprehensive review, McIntosh (1990) documented fewer than 10 diplodocid skulls from the Morrison Formation of the United States (Table 1). These include two of *Diplodocus longus*, two of *D. carnegii*, and one of *Apatosaurus louisae*, considerably fewer than sauropod species known from postcrania from this same interval, even given the oversplit state of Morrison Formation sauropod taxonomy whereby McIntosh (1990) recognized as many as ten species of diplodocids. The last decade has not substantially added to this record, which was developed over 120 years of collecting, although another skull of *Apatosaurus* is now known (Connely, 1997).

Consequently, any sauropod skull material from the Morrison Formation is potentially the first record of a particular taxon. Therefore, NMMNH P-26084 is important because it is both the only sauropod skull and jaw material recovered from the Jurassic of New Mexico and one of less than a dozen Morrison Formation diplodocid skulls known. The preserved skull is too incomplete to assign to a specific genus, but the numerous sauropod postcrania from the locality should, when prepared, facilitate genus-level identification of the sauropod(s) at the Peterson quarry. Although some of the preserved teeth were clearly unerupted, the presence of more than 30 teeth suggests that nearly the entire dentition was preserved, and recovery of additional sauropod teeth from the Peterson quarry suggests that more sauropod skulls may be found there in the future.

To date, less than a quarter of the material recovered from the Peterson quarry has been prepared. Clearly, as more of this material is prepared, our knowledge of this fauna will continue to increase. However, the uniqueness of the site in preserving both sauropod skull material as well as a large allosaurid has already vindicated the extensive effort of the BLM and NMMNH, to support this excavation.

ACKNOWLEDGMENTS

All excavation, fossil recovery, and data collection at the Peterson quarry has been conducted by volunteer crews, directed by Rodney and Ronald Peterson, working over the last 11 years, so that over 5200 volunteer hours have been dedicated to collecting dinosaur bones from this site. Numerous volunteers have dedicated countless hours to preparing these bones. Thomas Benson expertly prepared the diplodocid skull material illustrated here. The United States Bureau of Land Management, particularly Mike O'Neill, have provided significant logistical support of efforts at the Peterson quarry, which is located on lands administered by BLM. Discussions with A.K. Behrensmeyer and other visitors at an earlier presentation of this material (Peterson et al., 1999b) influenced the ideas presented here.

TABLE 1. Morrison Formation sauropods (after McIntosh, 1990)
(* indicates specimens with skulls or partial skulls)

Brachiosauridae
Brachiosaurus altithorax Riggs 1903
Camarasauridae
Camarasaurus supremus Cope 1877*(braincase)
C. grandis Marsh (1877)*
C. lentus Marsh (1889)
Diplodocidae
Apatosaurus ajax Marsh 1877 *(braincase)
A. excelsus Marsh 1879 (=*Brontosaurus*)
A. louisae Holland 1915*
Barosaurus lentus Marsh 1890
Diplodocus longus Marsh 1878b*
D. carnegii Hatcher 1901*
D. hayi Holland 1924*(braincase)
D. lacustris Marsh 1884 (jaw with teeth only)
D. hallorum (Gillette) 1991 (=*Seismosaurus*)
Haplocanthosaurus priscus (Hatcher, 1903)
H. delfsi McIntosh and Williams 1988
Fragmentary or questionably valid taxa
Amphicoelias altus Cope 1877
Supersaurus vivianae Jensen 1985
Dystrophaeus viaemalae Cope 1877
Dyslocosaurus McIntosh 1992

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APPENDIX: DESCRIPTION OF MEASURED SECTION

Peterson Quarry (L-3282)

Section measured at the Peterson quarry, NMMNH locality L-3282. Measured on northerly trend from UTM zone 13, 3897311 N, 0305883E by S.G. Lucas and A.B. Heckert.

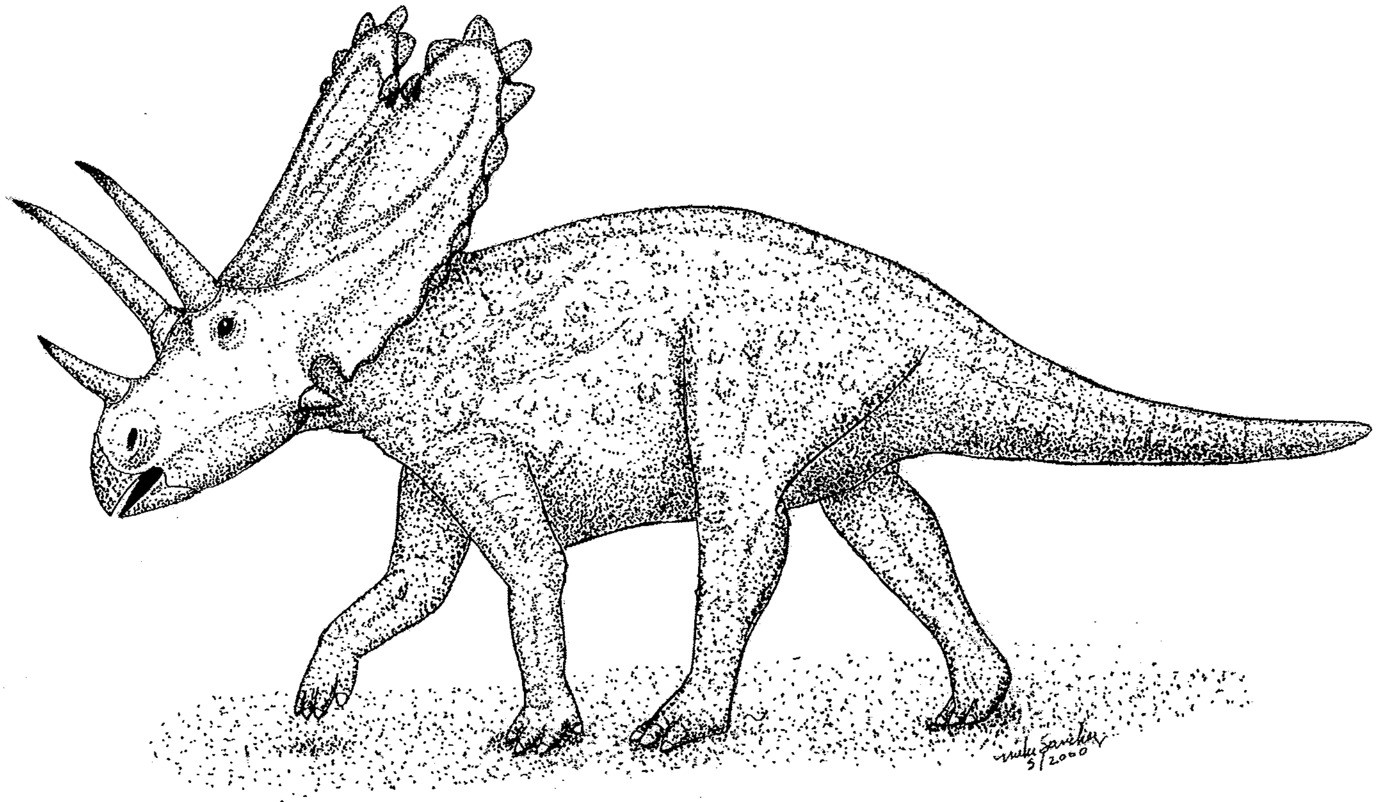
Morrison Formation:

Jackpile Member:

unit	lithology	thickness (m)
7	Sandstone; very pale orange (10YR8/2); fine-grained; subrounded; kaolinitized, moderately well-sorted quartzarenite to subarkose; trough crossbedded; not calcareous; forms a 6 m+ cliff.	not measured

Brushy Basin Member:

unit	lithology	thickness (m)
6	Mudstone; same colors and lithology as unit 4.	14.3
5	Sandstone; yellowish gray (5Y7/2); fine-grained, subrounded, well-sorted sublitharenite; laminar; some bioturbation at top; not calcareous; forms a ledge.	0.3-0.5
4	Mudstone; mostly greenish gray (5GY6/1) with some moderate reddish (10R4/6) bands; bentonitic; silty; not calcareous to very slightly calcareous.	9.2
3	Primary bone-bearing horizons, subdivided as follows:	
3D	Sandstone; yellowish gray (5Y8/1) fresh; weathers to olive gray (5Y3/2); fine to medium-grained, subangular to subrounded, well-sorted subarkose; trough crossbedded; not calcareous.	0.9
3C	Sandstone; yellowish gray (5Y7/2); medium-grained, subangular; well-sorted subarkose; trough crossbedded; scours into underlying unit; some clay pebbles at base; not calcareous.	0.6
3B	Sandstone; yellowish gray (5Y7/2); fine-grained, sub angular, well-sorted sandstone; bioturbated; calcareous.	0.7
3A	Bone-bearing horizon; sandstone; grayish yellow green (5GY7/2); fine- to coarse-grained, subangular, poorly sorted subarkose; trough crossbeds; some scours and clay pebbles at base; very calcareous; floors arroyo at L-3282. Unit 3 is 3.3 m thick, total.	1.1
2	Sandstone; yellowish gray (5Y7/2); fine- to coarse-grained, subangular, moderately poorly sorted subarkose; trough crossbedded; locally pebbly; not calcareous; floors arroyo to northeast of locality 3282.	4.5
1	Mudstone; greenish gray (5GY6/1); smectitic; silty; not calcareous; locally exposed below unit 2.	not measured



Restoration of *Pentaceratops*, by Michael Sanchez.